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ULTRASONIC TEMPERATURE MEASURING DEVICE

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prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Third Quarterly Progress Report

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ABSTRACT

During the third quarter, work proceeded on an evaluation of both piezoelectric and magnetostrictive transducers at both high and low frequencies. In addition, the design of the capsule for the radiation test has been agreed upon.

Analysis of radiation effects has eliminated iridium as a possible sensor material. The calculations indicate that Cb, Mo and Re can be safely tested ultrasonically, without a hot cell, within two months after irradiation.

Preliminary tests have been conducted at high temperatures in an rf oven. This oven is one of several being considered to provide a high temperature carbon free environment in which radiation effects on sound velocity can be measured.

Additionally, construction of an automatic pulsing and receiving unit has begun.

I. SUMMARY

During the third quarter, work proceeded on the first four steps in the program.

Step I consists of room temperature preliminary ultrasonic measurements, and capsule design and tests. Both piezoelectric and magnetostrictive transducers are being evaluated, as well as both high and low frequencies. Refractory wires have been butt-welded to themselves and other wires.

The design of the unheated, unmonitored radiation experiment capsule has been completed and approved by Babcock and Wilcox.

Step II is the radiation experiment and analysis. Iridium has been excluded as a possible sensor material, due to the effects of radiation. Calculations show that Cb, Mo and Re can be safely tested relatively soon after irradiation without requiring a hot cell. Ultrasonic testing of irradiated W and Ta would require a hot cell due to long life isotopes.

Tests of wire uniformity have begun.

Step III includes high temperature tests and analysis. Mo was heated to its melting point in an oxyacetylene flame. End echo amplitude remained approximately constant until near the melting point.

In order to prevent carbiding of the sensor wire during high temperature testing to determine the effects of radiation it has been necessary to consider various contaminant-free high temperature sources. Preliminary tests have utilized an rf oven.

Step IV is the construction and testing of the pulser. The pulsing and receiving unit is presently under construction and will be compatible with the transducers under development.

II. PROGRESS ON STEPS I, II, III AND IV

A. Room Temperature Preliminary Ultrasonic Measurements and Capsule Design and Test

1. Materials

Previously, only elements with melting point greater than 5000° R have been considered as possible sensors. However, by slightly relaxing this cutoff temperature[1] it is possible to include columbium (M. P. = 4934° R) in the list of candidate materials. The materials that are now being investigated are W, Re, Ta, Mo and Cb, and W-Re alloys.

2. Transducer Optimization

a) Introduction

The thin wire technique can be used with either extensional or shear wave modes. In order to obtain an optimum system, we have studied the design of both piezoelectric and magnetostrictive transducers, each of which can operate in either mode. Figures 1 and 2 show some of the designs studied.

b) Magnetostrictive

The magnetostrictive transducers shown in Figure 1 operate at about 300 kHz. With a 3 in. sensor length and the automatic device being developed the temperature should be measurable to within 1% at this frequency. At 1 MHz, the pulse length in the wire is about 0.1 in. for a shear mode, or 0.2 in. for an extensional mode. To launch such short pulses magnetostrictively requires the coil length plus its stray field to be shorter than about 0.1 in. This imposes severe limits on the maximum number of turns that can be closely coupled to the magnetostrictive element,* or conversely, limits the upper frequency to about 2 MHz at present. Skin effect also reduces the effectiveness of magnetostriction at high frequencies.

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*See also V. Ramakrishna, Electro-Techn. 45-47 (Aug. 1965); F. Yorgg, Electronic Prod. 27-62 (Dec. 1963).

c) Piezoelectric

On the contrary, use of a piezoelectric transducer permits tight coupling to the thin wire at high frequencies of interest. Frequencies as high as 5 MHz might ultimately be practical, in some instances, depending on the wire's transmission characteristics.* Two MHz is practical at present, with about 10 db less insertion loss introduced by the piezoelectric unit than by the magnetostrictive unit at this frequency.

Figure 2 shows piezoelectric transducers presently under study. The three piezoelectric torsional mode transducers, including damping members, have been constructed by Andersen Laboratories, for use at 0.5, 1 and 2 MHz. These transducers will be bonded to the centerless ground Mo impedance matching cones, shown in the foreground, which in turn will be resistance welded to 0.020 in. diameter Mo wires. The jig permits accurate assembly of transducers and serves as a shielded housing for tests.

d) Torsional Mode

Previous progress reports have indicated the advantages of using high frequency pulses, and suggested the possibility of a coiled sensor for increased accuracy and better localization of the temperature reading. Some of the limits on maximum frequency and minimum radius of curvature are discussed in a book by C. F. Brockelsby, et al [2] and in a recent review article by S. Davidson.[3] For torsional waves, which are most commonly used in ultrasonic wire delay lines up to 2 MHz, one upper limit on frequency is imposed by the wire's diameter, shear modulus and density, according to the equation

$$f_c = \frac{5.136\sqrt{G/\rho}}{\pi d} = \frac{5.136\, V_T}{\pi d} \approx \frac{V_T}{r}$$

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*See, for example, R. Lowrie and A. Gonas' work at 5 to 6.5 MHz up to 3700°R in a 3/4 in. diameter notched bar of polycrystalline tungsten. Tech. Rpt. No. C-27, Union Carbide Res. Inst. (Jan. 1965).

where f_c = maximum frequency that can be transmitted down the wire,

G = shear modulus

ρ = density

$V_T = \sqrt{G/\rho}$ = shear (torsional or transverse) wave velocity

d = wire diameter = 2 r.

Table I lists f_c in five metal wires, of 0.020 and 0.040 in. diameters. Since V_T decreases at the elevated temperatures of interest, f_c is actually determined by the sound velocity at the maximum temperature experienced by the wire. Near 5000° R, V_T may be about half the room temperature value. Future high temperature tests will determine this limit more precisely. (See page 13).

Taken alone, Table 1 would suggest the use of wire diameters less than 0.020 in. to increase f_c as high as desired. However a second limit on maximum frequency is imposed by the scattering and absorption characteristics of the wire at high temperature. (Additionally, surface characteristics of some wires, such as Re, are better in larger diameter wires). Commercially available wire delay lines operate up to 2 MHz. It is unlikely that long refractory wires could operate at high temperature much above this practical frequency limit, and in fact lower frequencies may be required to overcome attenuation. One problem with the torsional mode is that supports and feedthroughs are relatively attenuating compared to the extensional mode.

e) Extensional Mode

Use of the extensional mode also remains a possibility. The extensional wave velocity is faster than the shear wave velocity by the ratio $\sqrt{E/G} = \sqrt{2\sigma + 2}$ where E = Young''s modulus, G = shear modulus and σ = Poisson's ratio. For $\sigma = 1/3$, $\sqrt{2\sigma + 2} = 1.63$, which means wires of $\sigma \approx 1/3$ can be interrogated or pulsed at a repetition rate $\approx$ 60% faster using extensional mode than with a shear mode. In some cases the extensional mode is less subject to attenuation by support or packing media. The extensional mode was used by Bell, Thorne et al in their work, and by Parametrics, Inc. for the thin wire measurements reported earlier. This mode has found rather limited use in delay lines because dispersion in long wires becomes excessive. However, Showell et al [4] described a 1 msec Permendur extensional wave line, which used a path of ~20 ft at 1 MHz. We found similar results on refractory wires tested at 1 MHz; i.e., pulse dispersion was not a problem.

f) Coiling

By coiling, it is possible to compress a long sensor wire into a short sensor length. Normally, ultrasonic torsional mode wire delay lines designed to operate with ~1 MHz video pulses are coiled in approximately 6 to 10 in. diameter coils, to avoid dispersion. However, by coiling a wire on a 3/8-18 threaded mandrel it is possible to compress a 10 in. wire in a 1/2 in. length. This was done with a 10 foot length of 0.040 in. diameter Mo wire, in order to test this concept. Extensional wave echoes were obtained from the beginning and end of the coil with 1 MHz rf pulses, and a 6 foot lead-in. Coiling has also been successfully accomplished with Cb and W (coil diameter ≈ 1 in.). In the case of tungsten, it was necessary to heat it above the brittle ductile transition temperature before coiling.

To support coils at temperatures close to the melting point, refractory powders such as MgO, BeO or ThO_2 may be used. This concept has been demonstrated at room temperature. As long as the powder is not tamped too tight, the sound coupled out of the wire is negligibly small.

If low frequencies of the order of ~ 0.3 to ~2 MHz are indeed required to overcome attenuation, then a coiled sensor will not be practical for the present installation. However, the coiled sensor concept is still valid for calibration or test purposes, to increase the kink to end distance to ~10 in. or make use of smaller uniform hot zones. The concept would also be applicable where larger diameter holes are allowable, or where a surface temperature is required, and a pancake coil sensor could be tolerated.

Experiments with a commercial wire delay line at 0.5 MHz (torsional mode) showed that kinks within 1 in. of the wire's end could easily be resolved, and further, that coils of ~3/8 diameter introduced no reflections. (Ratio of radius of curvature to wavelength ≈ 2). The 0.020 in. diameter Ni-Span-C *wire could be coiled on a 0.020 in. diameter mandrel, but this tight coiling

*One of several standard delay line wire materials.

produced spurious echoes. However, kink and end echoes could still be resolved with some difficulty.

It may be mentioned that no difficulty was experienced in coiling 0.020 in. diameter Mo. tightly around a 0.020 in. diameter Mo mandrel. This tight coil compresses about six inches of wire into a one inch long, 0.060 in. O.D. coil of 50 turns. This coil has not yet been tested acoustically.

3. Transducer Specifications

In consideration of the above results in the transducer optimization study, it was decided to tentatively specify a 3 μ sec pulse width* magnetostrictive extensional mode transducer system, as this offered the best performance at this time. The specified transducers consist of separate transmitting and receiving coils, both in a shielded capsule (See Figure 1). The equivalent circuit of the transmit coil is a 1.5 μh inductance in series with an 0.21 Ω resistance; the receive coil is represented as a 450 μh inductance series with a 67 Ω resistance. When such coils were tested with 10 ft Mo and Re sensor wires having a kink 3 in. from the end, the received signal levels from the kink and end were about 3-5 mv peak, with a signal to noise ratio of at least 2 to 1.

Work will continue to provide a narrower pulse to obtain greater accuracy in the automatic temperature indicator. Use of a torsional mode also contributes to improved accuracy since the transit time for a given sensor length is about 60% longer than in an extensional mode.

It appears that a torsional unit consisting of a highly damped 2 MHz piezoelectric transducer would be a promising candidate for future studies, after completion of the welding studies described in Section 5.

4. Impedance Matching

For a wave in a thin wire the mechanical impedance[5] $Z_m = \rho VA$, where

*Pulse width is the elapsed time between zero crossings of a positive video pulse. The pulse shape is such that this width is equal to about twice the pulse rise time. Also, the "band width" is the reciprocal of twice the pulse rise time).

ρ = density

V = wave velocity

A = cross sectional area

For a wave being transmitted from one medium to another the energy transmission coefficient, T, is given by:

$$T = \frac{4 Z_1 \quad Z_2}{(Z_1 + Z_2)^2} \quad .$$

If $Z_1 = Z_2$ then T = 1 and no energy will be reflected. This is important for the present study since it may be necessary, or desirable, to use different materials for sensor and lead-in. Figure 3 and 4 are nomograms in which the materials of interest are located according to their density and extensional and transverse velocities, respectively. Constant characteristic impedance lines (ρV = const.) are shown parallel and one decade apart. These nomograms are for room temperature conditions.

The elimination of reflections is desirable since any reflection takes acoustic energy away from the signal and introduces a possible confusing echo. In the automatic system being developed the unwanted reflection will be gated out electrically. The usually undesirable reflection, however, may be used to advantage if a short sensor is attached to a lead-in line, the joint discontinuity replacing the kink.

Besides choosing materials to minimize impedance mismatch, it is also possible to produce an impedance matching section of varying cross section. This is shown in Figure 2. The conical section matches the mechanical impedances of a piezoelectric crystal on one end and the sensor wire on the other end. This technique is currently being used in commercial ultrasonic delay lines.

5. Butt Welding

As previously stated, in order to use a piezoelectric transducer it may be necessary to butt weld a wire to an impedance matching cone or to another wire. The materials to be welded may be the same or different, depending on the length of lead-in, final sensor material and temperature distribution along the lead-in. For a long lead-in a relatively inexpensive ductile wire may be used. With this in mind the Schlatter S 1-1/2 Butt Welding Machine was evaluated experimentally.

Using the Schlatter welder it was possible to achieve satisfactory welds with many combinations of the candidate materials. In addition, it was possible to weld nickel, a magnetostrictive material, to Cb and Mo. This welder may be modified, by the addition of a flowing inert gas system, to weld all of the materials of interest. The purpose of the inert gas is to prevent oxidation of the materials.[6]

6. Capsule Design

The design of the capsule for the radiation experiment was submitted to Babcock and Wilcox and has been agreed upon. The capsule is commercially pure Al, 6 in. long and ~ 1-3/4 in. diameter, and is welded closed at both ends. The flux will be monitored by conventional Al-Co and Fe wires placed within the capsule.

The radiation experiment is discussed next.

B. Radiation Experiment and Analysis

On February 16, Babcock and Wilcox personnel visited Parametrics, Inc., to review radiation effects, handling hazards, and the conduct of the forthcoming radiation test. Independent calculations performed by Babcock and Wilcox and by Parametrics, Inc., indicated that radiation effects and handling hazards will be minimum in pure grades of Re, Mo and Cb (these three materials, incidentally, are all ductile at room temperature, making it convenient to coil relatively long lengths into the test capsule). Isotopes with long half-lives and high activity render Ta and W more difficult to handle. Several W-Re alloys will be tested. Use of alloys would appear to depend on the behavior of their separate constituents, i.e., if W and Re are acceptable individually, their alloys should likewise be acceptable, from the radiation standpoint.

The calculations indicated that after irradiation, Cb, Mo and Re could be safely handled, without shielding, in 0, 30 and 60 days, respectively. W, Ta and the W/Re alloys could be ultrasonically tested in a hot cell.

Iridium has also been considered, but due to the extremely high activity, long-lived isotopes which would be produced at the anticipated irradiation levels, its use in the present application is unwarranted, although it has a melting point = 4909° R.

The objective of the radiation test is to determine the effects, if any, of irradiation on the velocity of sound in the sensor material. In order to obtain this information it is first desirable to determine the uniformity of unirradiated wire. This will be done by measuring the sound velocity in the wires at room and elevated temperature.

Uniform lengths will be cut into at least two equal lengths. The wires will be kinked and a velocity vs temperature graph will then be generated for both samples. One sample will be irradiated and one retained as a control. This will be done for the wire materials of interest.

A test was run to determine if the cold working done by coiling and uncoiling samples has any effects on velocity. The sound velocity in 0.020 in. diameter Cb and Mo was measured at room temperature, before and after each wire was coiled and uncoiled. The velocity did not change significantly.

C. High Temperature Tests and Analysis

In order to use the thin wire system in the graphite resistance oven it is necessary to prevent carbiding of the wire specimens. This is difficult above 3500 to 4000°R. Nevertheless, approaches are being investigated by many organizations in conjunction with thermocouple work. Because of the difficulty of preventing carbon contamination in a graphite oven, three additional approaches of obtaining high temperatures are being undertaken. These approaches eliminate carbon from the oven and require heating the sample by means other than by radiation from a graphite resistor. Two of the methods being developed are rf (induction) and dc heating of a refractory metal tube. The third approach uses the muffle tube concept.

1. Muffle Tube Concept

In order to use the high temperature capabilities of the graphite oven, a metallic muffle tube, coated on its exterior surface with an insulating refractory material, has been considered. A 3/8 in. diameter Ta tube, 12 in. long, coated for 8 in. with zirconium diboride, will be evaluated in the graphite oven, to test this material combination as a muffle tube. Details of this scheme are shown in Figure 5. With this scheme an inert gas flows over the test wire at a low flow rate. This removes carbon without substantially cooling the test sample. The outside of the Ta tube is coated with ZrB_2, which is reportedly stable in the presence of carbon[7] and which should retard carbon diffusion into the Ta. A ZrO_2 inner sheath, in powder, bead or tubular form, provides a further means of reducing diffusion of carbon to the test sample. The flowing gas method has been successfully used by Forrest and Hall[7] and is being used in the NERVA project to about 4500°R.[8]

2. DC Oven With Refractory Metal Heater

A dc oven employing a Ta or Mo heater has been designed and partly constructed. The heater is 1 in. diameter, 12 in. long, and of "C" shaped cross section, the wall thickness being 0.020 in. The C shape provides visual access for pyrometry all along the axis, and also permits detailed observation of thin wire test specimens. The oven will be operated under vacuum, within a reflectively coated fused silica tube. Using the Ta heater, of melting point =5885°R, operation up to about 5300°R should be possible. At this temperature, its resistivity is about 100 μ ohm-cm, and its resistance from end to end, about 0.01 ohm. To develop 10 kw, 1000 amperes are required. Thus, electrical operating conditions are similar to the graphite oven used previously. A uniform hot zone about 3 to 4 in. long is expected in this design.

3. Rf Oven With Refractory Metal Susceptor

Another approach to a contaminant-free high temperature source employs a Ta tube susceptor inductively heated by an rf generator. A 4 in. long susceptor was cut from a 3/4 in. diameter tube of 0.020 in. wall. This tube is considered "thin walled" at rf frequencies for which the wall thickness ($t = 0.020$ in.) is much less than the skin depth, provided $t/(a-t) \ll 1$, where a = outer radius of tube. According to Stansel[9] maximum electrical efficiency is obtained at the frequency

$$f = \frac{44 \times 10^6 \rho}{(a-t)\, t} \quad \text{Hz}$$

where ρ = resistivity, ohm-cm. In the present example, for temperatures near 5000°R, $f \approx 110$ kHz. At this frequency, the skin depth is about 0.05 in., or more than twice t. The same result, $f \approx 110$ kc, can also be obtained graphically using Tudbury's[10] nomogram, which also shows that this Ta tube, at 110 kHz, reflects about 2.4 times more resistance into the rf work coil (primary) than a solid Ta bar at the same frequency and temperature. For test purposes, it is interesting to note that nichrome has essentially the same resistivity from room temperature to at least 1300°K as Ta does near 5000°R.

Initial tests have been conducted on the Ta susceptor at 110 kHz, but more work is required to establish the power requirements for achieving temperatures up to 5000°R.

4. Measurements

A high temperature test was conducted with 0.070 in. diameter Mo wire at 500 kHz. An extensional mode wave was transmitted down 5 feet of the wire as the 3" kink-end distance was heated by an oxyacetylene flame. The end echo emplitude was approximately constant until near the melting point, where the signal level decreased.

Commercial feedthroughs for the thin wire that will hold vacuum and pressure have been evaluated. The feedthroughs tested (Conax MHC-040-A-2-L and MHC-040-A-2-T) had either lava or teflon seals. When assembled, both seals absorbed such a large part of the transmitted energy that they were unsuitable for this system. A rubber stopper, however, has been found suitable for a vacuum seal and has been used in tests to $\sim$ 2500°R. Conax feedthroughs using neoprene inserts are also suitable acoustically.

D. Construction and Testing of Pulser

Construction of the automatic pulsing and readout unit has begun at the Gordon Engineering Company. This unit will have both analog and digital readouts, plus an output to a recorder. Initially, the unit will be adapted to magnetostrictive transducers.

Table I

Maximum frequencies for propagating torsional mode in thin wires.

Wire Material	Melting Point ^{o}C	^{o}R	V_T at Rm Temp in. / μ sec	$V_T/2$ in. /μ sec	f_c at Rm.Temp MHz d=0.02"	0.04"	$f_c/2$ MHz d = 0.02"	0.04"
W	3400	6630	0.113	0.057	9.4	4.7	4.7	2.4
Re	3180	6220	0.113	0.057	9.4	4.7	4.7	2.4
Ta	3000	5885	0.080	0.040	6.7	3.4	3.4	1.7
Mo	2620	5200	0.132	0.066	11.0	5.5	5.5	2.8
Cb	2500	4985	0.080	0.040	6.7	3.4	3.4	1.7

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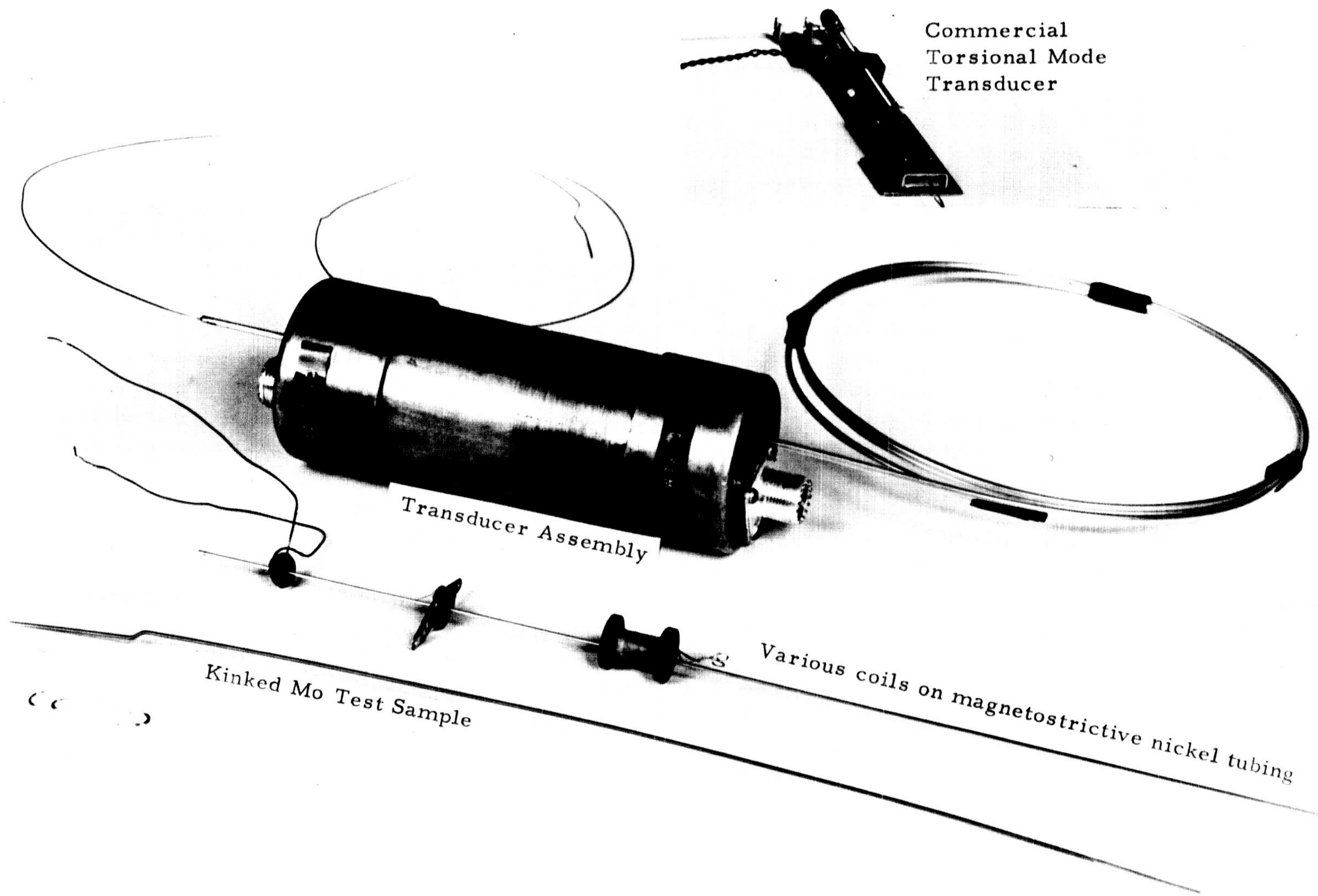

Figure 1. Magnetostrictive Transducers

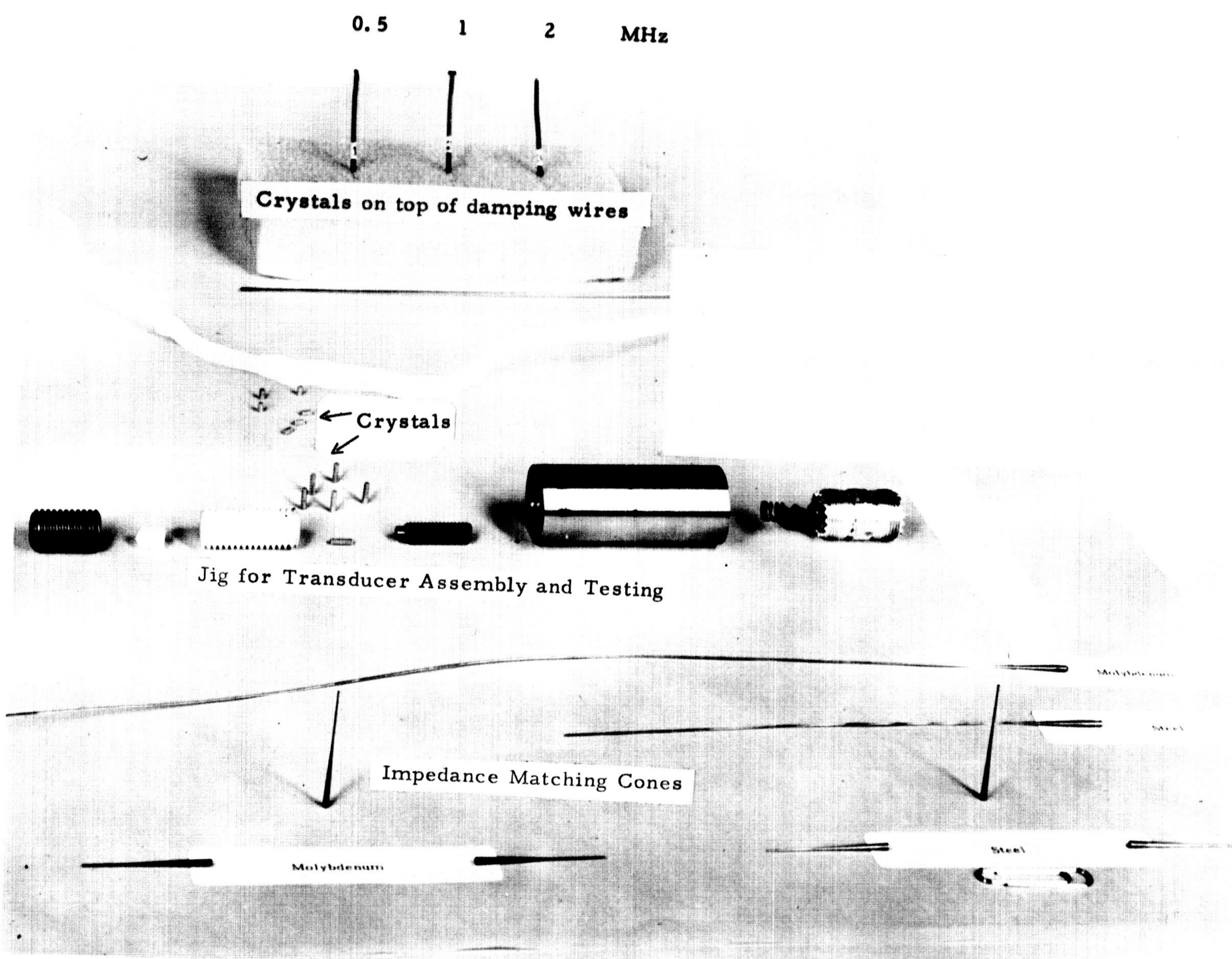

Figure 2. Piezoelectric Transducers

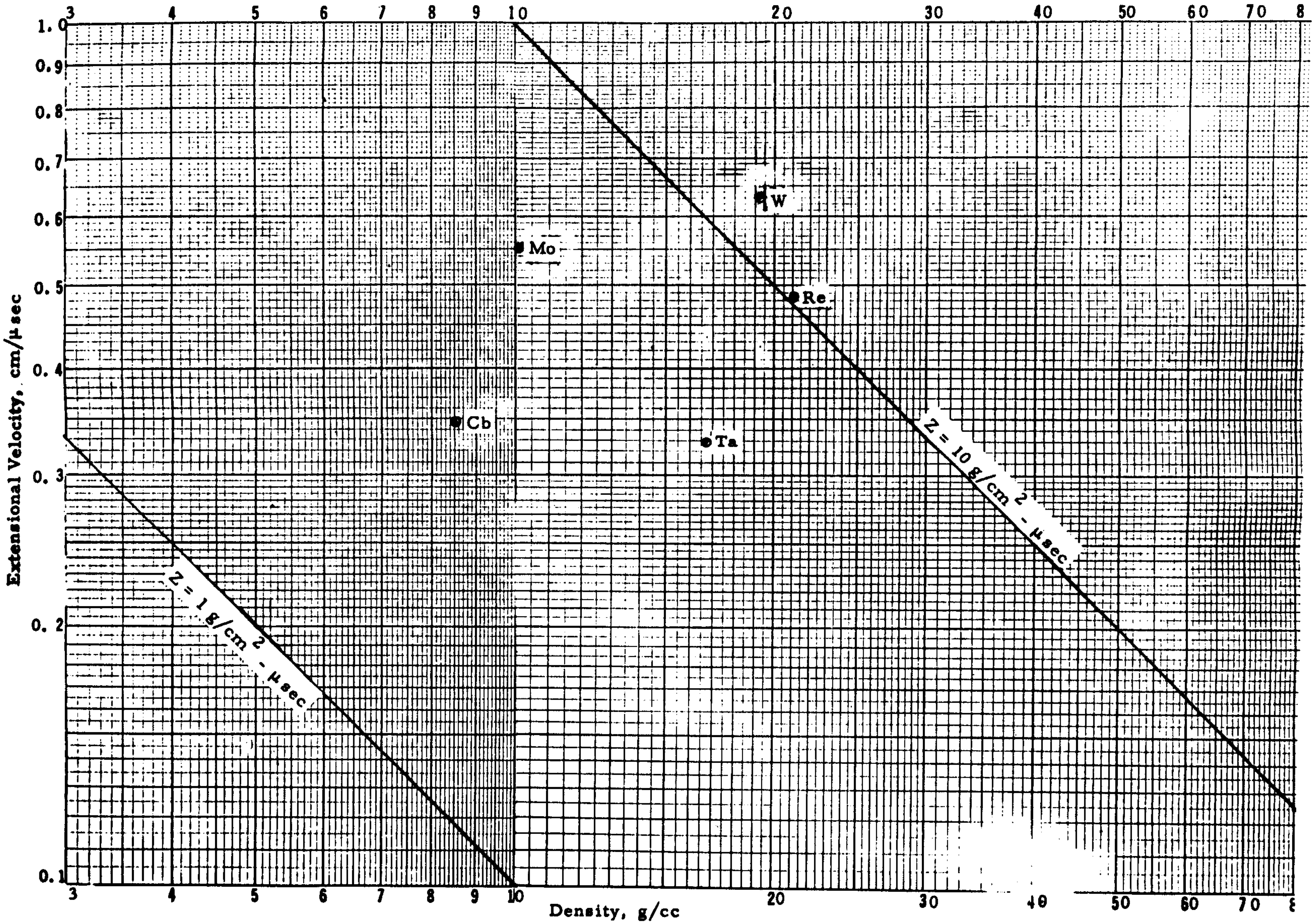

Figure 3. Extensional Wave Impedance Nomogram

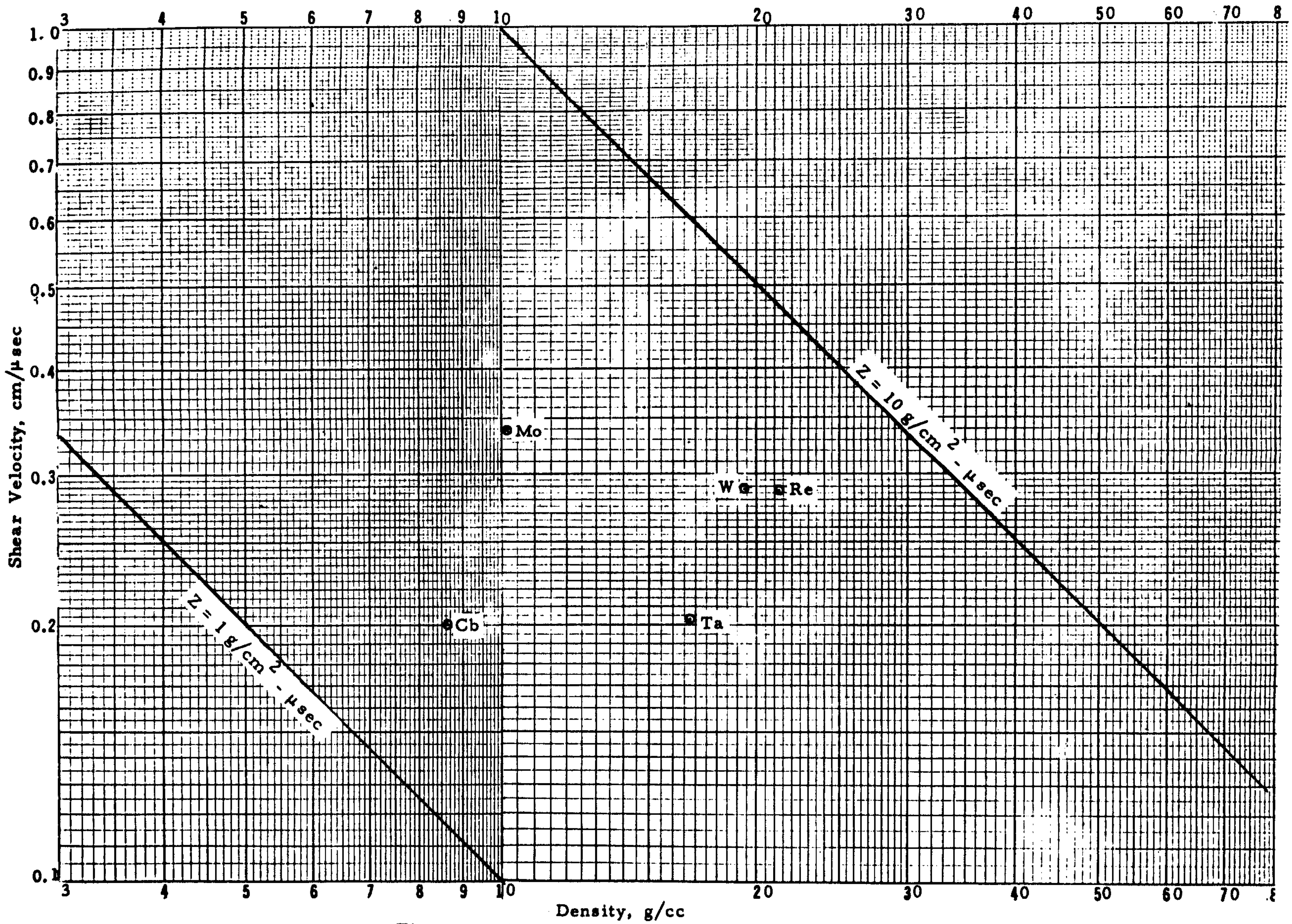

Figure 4. Shear Wave Impedance Nomogram

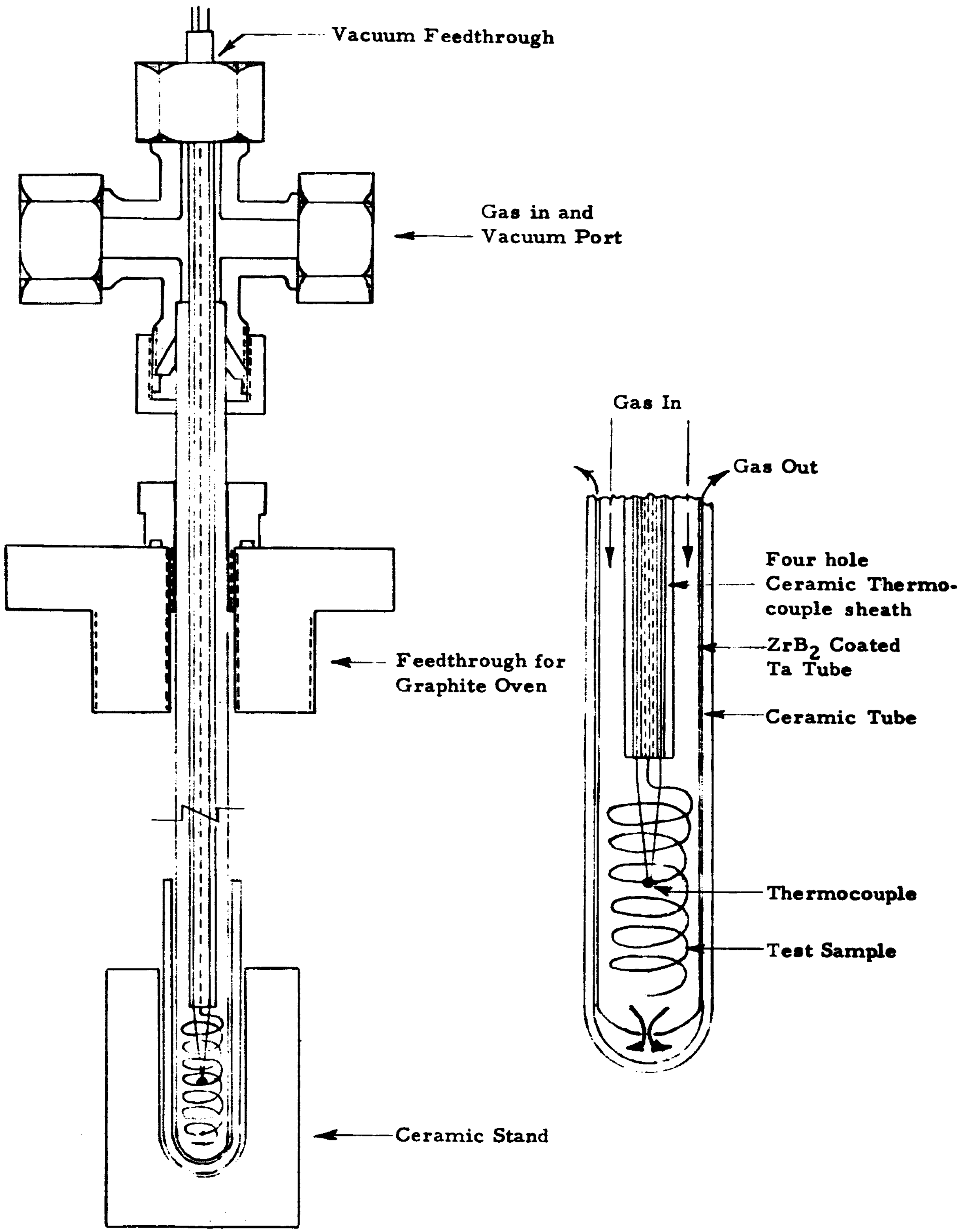

Figure 5. Carbon Contamination Prevention Scheme